The Importance of UV Capabilities for Identifying Inhabited Exoplanets with Next Generation Space Telescopes

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ABSTRACT: The strongest remotely detectable signature of life on our planet today is the photosynthetically produced oxygen (O_2) in our atmosphere. However, recent studies of Earth's geochemical proxy record suggest that for all but the last ~500 million years, atmospheric O_2 would have been undetectable to a remote observer—and thus a potential false negative for life. During an extended period in Earth's middle history (2.0 – 0.7 billion years ago, Ga), O_2 was likely present but in low concentrations, with pO_2 estimates of ~ 0.1 – 1% of present day levels. Although O_2 has a weak spectral impact in reflected light at these low abundances, O_3 in photochemical equilibrium with that O_2 would produce notable spectral features in the UV Hartley-Huggins band (~0.25 μm), with a weaker impact in the mid-IR band near 9.7 μm. Thus, taking Earth history as an informative example, there likely exists a category of exoplanets for which conventional biosignatures can only be identified in the UV. In this paper, we emphasize the importance of UV capabilities in the design of future space-based direct imaging telescopes such as HabEx or LUVOIR to detect O_3 on planets with intermediate oxygenation states. We use a coronagraph instrument model to show that the Hartley-Huggins O_3 UV band is detectable in reflected light for a low-oxygen exoplanet (pO_2=0.5% PAL) orbiting a Sun-like star at 10 parsecs with a 10-m telescope. We conclude by discussing strategies for mitigating 'false positives', i.e., O_3 produced by abiotic processes. More generally, this example highlights the broad implications of studying Earth history as a window into understanding potential exoplanet biosignatures.

1. Introduction and Relevance

The search for life beyond our solar system is a prominent goal within the NASA astrobiology program, emphasized in both the 2008 Astrobiology Roadmap and the 2015 Astrobiology Strategy. The rapid evolution of exoplanet science from detection to characterization studies and the discovery of planets in the habitable zones of nearby stars underscores the timeliness of this effort. The nearest and best chance for identifying life on exoplanets will be provided by large (30-m class) ground-based observatories and future 10-m class space-based direct-imaging telescopes. While the James Webb Space Telescope (JWST), set to launch in 2019, will provide an unprecedented opportunity to characterize exoplanets through phase curves, secondary eclipse observations, and transit transmission spectroscopy, space-based direct-imaging characterization of terrestrial exoplanets will have to wait for dedicated observatories such as the LUVOIR or HabEx concepts (e.g., Mennesson et al. 2016; Bolcar et al. 2017). The science and technology definition teams (STDTs) for both concepts are convening now, and as was the case for JWST, **broad determination of the required instrument capabilities for these missions will be made many years and perhaps decades before their launch dates**. It is therefore essential to accurately and swiftly identify the minimum capabilities for a direct-imaging observatory to accomplish top level objectives such as identifying inhabited planets (e.g., Stark et al., 2014).

The most commonly referenced biosignature gases are O_2 and its photochemical byproduct O_3, due to O_2's exclusive biological production on Earth through oxygenic photosynthesis and the strong thermodynamic and kinetic disequilibrium it produces in the atmosphere (Des Marais et al., 2002). Technical studies of the feasibility of detecting O_2 with ground and space-based observatories are ongoing (Snellen et al. 2013; Rodler & López-Morales 2014). Alternative biosignature gases, surface signatures, and overarching frameworks have been proposed and should remain an important part of the conversation (see reviews in Schwieterman et al., 2018; Meadows et al., 2018, Catling et al., 2018, Walker et al., 2018, and Fujii et al., 2018); however it remains important to fully benchmark and examine O_2/O_3 signatures. We assert that Earth's history tells us that O_3, best detected in the UV, is a more sensitive and consistent indicator of planetary scale photosynthetic life than O_2, thus minimizing the potential for false negatives. In section 2 below we review Earth's oxygenation history as context for this assertion. In section 3 we examine the remote detectability of O_2 and O_3 through that history and model a test observation, and we discuss mitigation against false positives in section 4. We summarize our recommendations in section 5.

2. Earth's Oxygenation History

Although molecular oxygen (O_2) currently represents ~20% of Earth's atmospheric mass, the amount of O_2 in our atmosphere has evolved dramatically over time. Indeed, for the vast majority of Earth history, atmospheric O_2 levels were orders of magnitude below those characteristic of the modern Earth. During Archean time (3.8 – 2.5 billion years ago, Ga), the preservation of non-mass-dependent sulfur isotope anomalies in marine sediments fingerprints atmospheric O_2 concentrations well below 10^{-5} times the present atmospheric level (PAL; Farquhar et al., 2001; Pavlov & Kasting, 2002; Claire et al., 2006). The disappearance of sulfur isotope anomalies from Earth's rock record at ~2.3 Ga points to a rise in atmospheric O_2 (Luo et al., 2016), but a number of geochemical archives suggest extended periods of very low atmospheric O_2 well after this initial rise (Lyons et al., 2014; Planavsky et al., 2014; Cole et al., 2016). It is thus possible that atmospheric O_2 has been well below ~1% of the modern value for as much as 90% of Earth's evolutionary history. Just as the Archean Earth has been presented as an analog for Earth-like exoplanets (Arney et al., 2016), the subsequent Proterozoic eon (2.5 – 0.5 Ga), comparable in duration, provides an additional template for understanding the potential atmospheric states of habitable exoplanets—and the fundamental controls that should determine the evolving redox states for many complex planetary systems.

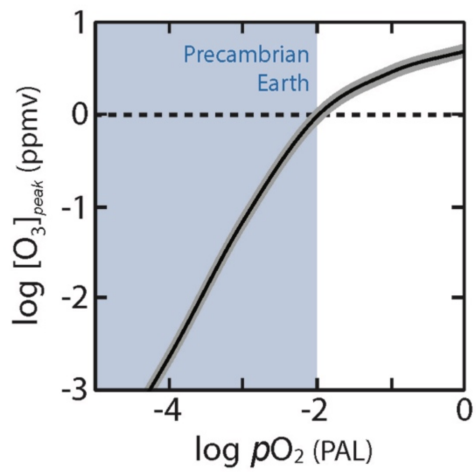

Figure 1 – O_3 abundance as a function of pO_2. *Calculation of peak stratospheric O_3 as a function of ground-level O_2 based results from Kasting and Donahue (1980). From Reinhard et al. (2017).*

3. Remote detectability of O_2/O_3 throughout Earth's history

Molecular oxygen (O_2) shows no significant spectral features at mid-IR wavelengths but absorbs strongly at the Fraunhofer A and B bands (0.76 and 0.69 μm, respectively) and at 1.27 μm. The most prominent of these features is the Fraunhofer A band, but this feature is expected

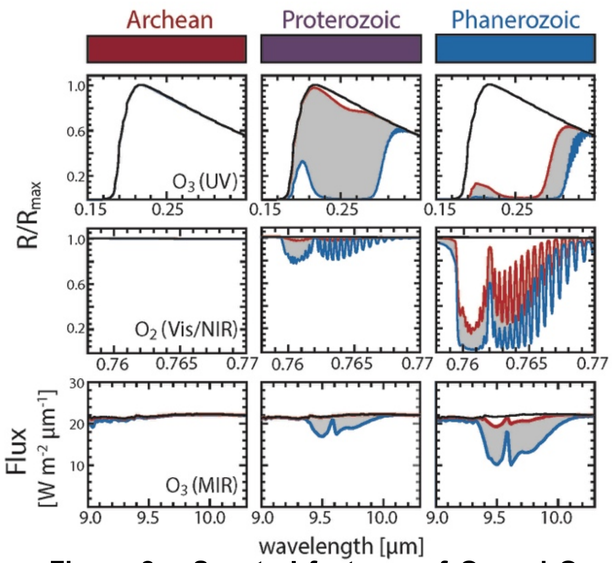

Figure 2 – Spectral features of O_2 and O_3 in the UV, Vis/NIR, and MIR. *Modeled planet spectra, at 1 cm^{-1} resolution, of the O_3 Huggins-Hartley band (0.25 µm), O_2-A band (0.76 µm), and 9.7 µm O_3 band at different geologic times assuming gas abundances informed by biogeochemical modeling and geochemical proxy constraints. Generated with the SMART radiative transfer model (Meadows & Crisp, 1996).*

to have appreciable depth only at atmospheric levels of ~1% PAL or higher (Des Marais et al., 2002; Segura et al., 2003). As a result, direct detection and/or quantification of O_2 would have been extremely challenging for all but the last ~500 million years of Earth's history (Reinhard et al., 2017).

However, O_2 can be detected by proxy through searching for signs of atmospheric O_3. On Earth, O_3 is produced in the stratosphere through photolysis of O_2 and recombination of O atoms with ambient O_2 molecules through the Chapman reactions. In addition, photochemical models demonstrate that the atmospheric abundance of O_3 shows strong dependence on atmospheric O_2 at oxygenation states significantly below modern values (see Figure 1), with the result that atmospheric O_3 levels are potentially a very sensitive indicator of surface O_2 production on terrestrial planets with low to intermediate oxygen levels compared to those present today.

Ozone has a number of significant spectral features at UV, visible, and IR wavelengths. In particular, O_3 absorbs strongly within the Hartley-Huggins bands at ~0.35-0.2 µm and the Chappuis bands between 0.5 and 0.7 µm and shows an additional strong absorption feature at 9.7 µm. **From the standpoint of detection, it is the near-UV Hartley-Huggins feature centered at ~0.25 µm that is most important, because it is sensitive to extremely low levels of atmospheric O_3.** This feature saturates at peak O_3 abundances of less than ~1 ppmv, corresponding to a background atmospheric O_2 level of around 1% PAL (Reinhard et al., 2017). This critical observation indicates that it may have been possible to fingerprint the presence of biogenic O_2 in the atmosphere using the Hartley-Huggins feature of O_3 for more than half of Earth's evolution, despite background O_2 levels that would have rendered direct detection of molecular O_2 extremely difficult. **Figure 2 displays simulated spectral observations of the UV Hartley-Huggins band, the O_2-A band, and the 9.7 µm O_3 band for upper and lower estimates of the concentrations of these gases during each eon** (data obtained from Table 1 of Reinhard et al., 2017). From Figure 2 it is apparent that the **most sensitive indicator of atmospheric O_2 is the UV O_3 band**, which would have created a measurable impact on Earth's spectrum for perhaps ~50% of its history to date, versus ~10% for O_2.

As a quantitative proof of concept for UV O_3 detectability at low planetary oxygenation states (e.g., pO_2=0.5% PAL), we simulate a 100-hour observation of such a planet around a sun-like star at 10 parsecs with a 10-m space-based telescope. To do this, we use the coronagraph noise model of Robinson et al. (2016), as implemented by J. Lustig-Yaeger in python[1]. The coronagraph model accounts for photon noise, read noise, dark current, photo speckle noise, thermal noise, and background from exozodical light (solar system equivalent assumed). Other observing parameters include a contrast ratio of C=1e^{-10}, telescope system temperature of T=260 K, and a spectral resolving power of R(λ/Δλ)=30. We show our results in Figure 3. **This figure shows that the long-wavelength edge of the Hartley-Huggins O_3 UV band is clearly characterizable with a LUVOIR-like architecture for mid-Proterozoic like O_2 levels.** In contrast, the simulated error bars are about an order of magnitude larger than the O_2-A absorption feature for the same oxygen mixing ratio, assuming R=100 but otherwise the same observing parameters (not shown).

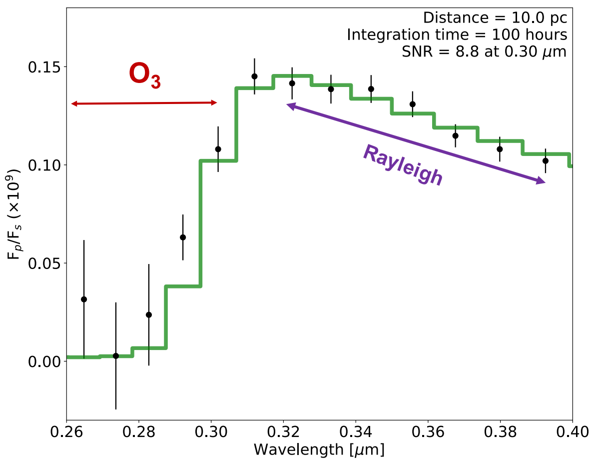

Figure 3 – Simulated observation of the O_3 UV band for a low-intermediate oxygen exoplanet. *Near-UV-blue spectrum of an Earth-sun system at 10 pc with atmospheric pO_2 of 0.5% PAL. The y-axis shows the planet-star contrast ratio with λ. Error-bars are 1σ.*

4. Mitigating against 'false positives'

Recent work has illustrated several scenarios for abiotic buildup of O_2 and O_3 in planetary atmospheres, such as through extensive hydrogen escape or robust CO_2 photolysis (see reviews in Meadows, 2017 and Meadows et al., 2018). One relevant observation is that in most cases, potentially detectable abiotic O_3 is more easily generated than detectable O_2 (e.g., Domagal-Goldman et al., 2014). However, the most compelling scenarios for 'false positive' O_2/O_3 biosignatures concern planets orbiting M-dwarf stars, which possess extended pre-main sequence phases (enhancing the probability of hydrogen loss and O_2 buildup) and high FUV/NUV flux ratios (enhancing the photolysis rate of O-bearing molecules such as CO_2). Fortunately, however, inner working angle (IWA) constraints for direct-imaging telescopes will favor the angular separation of habitable zone planets orbiting early K, G, and F type stars, where the processes that may produce abiotic O_2/O_3 are disfavored. In addition, the absence of certain UV/Vis/NIR spectral indicators, such as O_4 and CO, can help rule out these 'false positive' mechanisms (e.g., Schwieterman et al., 2016). The most plausible mechanisms for abiotic O_2/O_3 in planets orbiting solar-type stars is steady H-escape from thin, water-rich atmospheres lacking in non-condensing gases (Wordsworth & Pierrehumbert, 2014), in which case blue-near-UV wavelength capabilities will be important for estimating atmospheric mass through characterizing Rayleigh scattering. This positive dynamic is enhanced further by the higher photospheric temperatures of FGK stars, generating more near-UV flux and thus greater

[1]Implemented by J. Lustig-Yeager and available at https://github.com/jlustigy/coronagraph/

S/N at wavelengths relevant to O_3 characterization. Of course, assessing the host star's UV spectrum would also help directly constrain plausible photolysis rates and the resulting potential for abiotic O_2/O_3 (e.g., France et al., 2016). Thus, 'false positives' can be successfully mitigated by both target selection and multi-wavelength characterization of planet and star, **which would be aided by UV capability**. Further, mitigating against O_2 'false negatives' requires UV, or less effectively, MIR wavelengths inaccessible to the HabEx/LUVOIR concepts.

5. Discussion and Conclusions

Remote observations of Earth would have failed to detect O_2 for 90% of its history if limited to optical and near-infrared wavelengths. In contrast, **sensitivity to UV wavelengths would have allowed the detection of O_3, thus fingerprinting the presence of O_2 in our atmosphere for half its current lifetime.** There is no guarantee that habitable exoplanets will be like Earth or recapitulate its atmospheric evolution, but taking our planet as an informative example, it is clear that detection thresholds of pO_2 > 1% PAL or higher could eliminate the potential for life detection on planets with intermediate oxygenation states (10^{-5} PAL < pO_2 < 1% PAL). The LCROSS mission has detected O_3 in remote observations of Earth (Robinson et al., 2014) and **we have shown here that a LUVOIR-like architecture would have the capability to detect O_3 at low-intermediate pO_2 levels.** Additionally, UV wavelengths provide more favorable IWAs than optical or near-infrared observations for both coronagraph- and starshade-based designs (Seager et al., 2015; Robinson et al., 2016), allowing a greater number of planets to be surveyed and likely a larger biosignature yield (e.g., Stark et al., 2014). Importantly, 'false positive' O_3 biosignatures can be mitigated through target selection and multi-wavelength characterization (including UV), while O_2 'false negatives' cannot be eliminated without the UV.

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